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Publisher's version / la version de l'éditeur:
Proceedings 18th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'05, 1, pp. 409-419, 2005

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Vol. 1, pp 409-419, Potsdam, NY, USA, 2005.

VALIDATING MOTAN: RESULTS FROM MODEL-SCALE IMPACT TESTS WITH THE CCGS *TERRY FOX*

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ABSTRACT

This paper describes a model-scale test program that was designed to simulate the type of impacts that occurred during the Bergy Bit Trials. The model tests were conducted as part of a validation study of the inertial measurement system called MOTAN. Various types of controlled impact tests were conducted, during which global impact forces on a model of the *TERRY FOX* were compared to those measured independently on the impact plate. Percent differences between the two measurement systems ranged from 6.3 to 12.1% for the sway and pitch forces, depending upon whether the impact was symmetrical or oblique. The surge force from MOTAN was about 20% less than the longitudinal force measured on the impact plate. Results showed that MOTAN is a viable means of measuring ice-induced global impact forces and, therefore, is feasible for measuring loads on ships, at full-scale, during icebreaking operations.

INTRODUCTION

In June 2001 the Canadian Hydraulics Centre (CHC) used an inertial measurement system called MOTAN to measure global impact forces on the CCGS *TERRY FOX* as part of the Bergy Bit Impact Trials. Gagnon et al. (2002) describe the Trials, which involved conducting more than 150 distinct ship-ice collisions with 18 bergy bits, from 30 t to 22,000 t. MOTAN was used to measure whole-ship motions for each of those collisions, from which global impact forces were calculated. Johnston et al.

(2005-a) provide a detailed discussion of several collisions that resulted in the highest impact forces of the Trials. Because the ship-ice collisions involved a relatively small contact area (Ritch et al., 2005; Gagnon, 2005), it was possible to compare impact forces measured on locally instrumented areas of the port side of the bow to the global forces measured by MOTAN. There was good agreement between the global impact forces measured by MOTAN and the more locally measured impact forces on the ship's hull, as shown in Johnston et al. (2005-a).

Full-scale data from the Bergy Bit Trials provided one approach to validating global impact forces measured by MOTAN. A second approach to validating MOTAN was undertaken in 2003, when the National Research Council's Canadian Hydraulics Centre (CHC) and the Institute of Ocean Technology (IOT) collaborated to develop a model-scale test program, to be conducted at the IOT's facility in St. John's. The objective of the test program was to simulate the type of impacts that occurred during the Bergy Bit Trials; MOTAN was installed on a model of the *TERRY FOX* and it was used to conduct controlled collisions with an instrumented impact plate. A total of 30 symmetrical impacts and 34 oblique impacts were performed. This paper presents a succinct comparison of the impact forces measured by MOTAN and those measured on the instrumented plate. Johnston (2005) describes the model test program in greater detail.

MOTAN INERTIAL MEASUREMENT SYSTEM

The MOTAN (for MOTion ANalysis) inertial measurement system is a two-part package that is comprised of (i) a physical sensor unit and (ii) its associated computer software, as shown in Figure 1. The original MOTAN inertial measurement system was developed by the National Research Council's Hydraulics Laboratory to measure the motions of ships and floating structures in a wave basin or towing tank (Miles, 1986). Since that time, MOTAN has been redesigned and its software has been modified to allow global impact forces to be computed from measured whole-ship motions, at full-scale. To date, MOTAN has been used to measure global impact forces on USCGC *HEALY* (Johnston et al., 2001), CCGS *LOUIS S. ST-LAURENT* (Johnston et al, 2003) and CCGS *TERRY FOX* (Johnston et al., 2005-a, b).

The MOTAN sensor unit is a portable, lightweight instrument that has three accelerometers and three rotational rate sensors to measure ship motions in six degrees of freedom. The accelerometers measure the total ship acceleration (including the earth's gravity components) and the rate sensors measure the three-dimensional angular rotational rate of the ship along a body-axis coordinate system that moves with the ship (x', y' and z'). The sensor provides six analog voltage signals that are resolved along the x', y' and z' body axis of the ship.

Software called MOTAN (Figure 1) calculates transient motions of a full-scale ship due to ice impact forces using nonlinear equations of motion. The software transforms the accelerations and rotational rates measured by the sensor unit with respect to the body axis of the ship, to an inertial frame of reference (x, y, and z) that moves with the same average horizontal velocity as the ship, relative to the earth. Provided the ship behaves as a rigid body, the MOTAN software can be used to compute whole-ship motions at any point on the ship, regardless of where the sensor has been installed. Figure 1 shows the 18 elements output by the ship motion software: times series of the displacement, rate and acceleration in surge, sway and heave (translational motions) and pitch, roll and yaw (rotational motions).

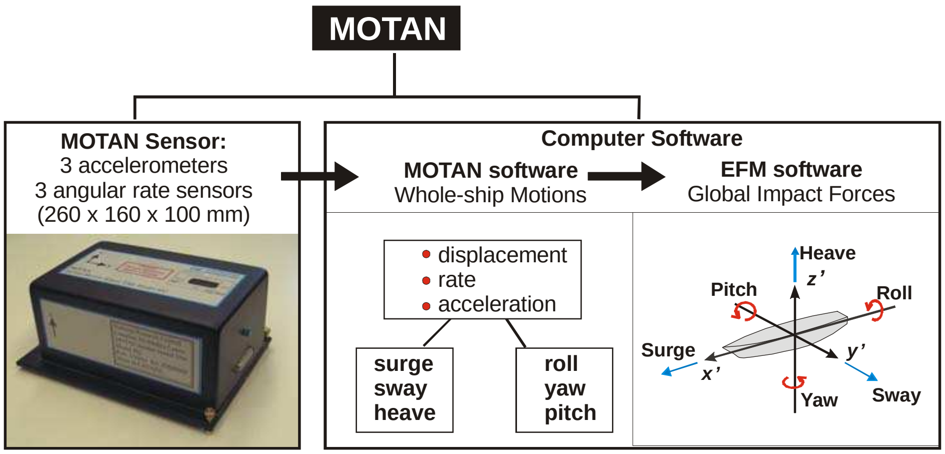

Figure 1 Schematic of MOTAN

In 2000, CHC developed a software package to calculate impact forces from select whole-ship motions (Johnston et al., 2001). As a first approach, that software used only heave and pitch motions to calculate a total vertical impact force and, as such was appropriate for symmetrical, head-on rams (where ship motions are primarily in heave and pitch). In 2002, an expanded version of the load calculation software was developed. The new software is called EFM (for Exciting Forces and Moments, Figure 1). Because EFM uses the entire suite of whole-ship motions to compute global impact forces, it is appropriate for both symmetrical and oblique impacts. The model program discussed in this paper was conducted to provide controlled test results with which to evaluate the accuracy of the EFM software.

EFM calculates three global exciting forces and three global exciting moments from the six linear, coupled differential equations included in Salvesen et al. (1970) and McTaggert (1997). The vectorial form of the six equations, which express ship motions in surge, sway, heave, pitch, roll and yaw, can be written as;

$$\{F\} = [M + A]\{\ddot{\eta}\} + [B]\{\dot{\eta}\} + [C]\{\eta\} \quad (1)$$

where:

F = exciting forces or moments

M = generalized mass matrix of the ship

A = hydrodynamic added mass matrix

B = hydrodynamic damping coefficient matrix

C = hydrostatic restoring force moment coefficient matrix

η = vectorial displacements in surge/sway/heave and roll/yaw/pitch

Calculating forces and moments with EFM requires information about the ship's characteristics, its hydrodynamic coefficients and its hydrostatic coefficients. McTaggert (1997) describes the coefficients in greater detail. To date, the Strip Theory Hydrodynamic Coefficients have been developed for *TERRY FOX* and two other full-scale icebreaking ships. The Coefficients, which depend upon ship speed and ship motion frequency, were determined for a wide range of frequencies, at operation speeds from 1 to 12 kt. Because the Coefficients were developed for *TERRY FOX* at full-scale, data from the model test program were scaled using a ratio of 21.8 (75 m length of *TERRY FOX*, full-scale (FS) to 3.44 m length of model, model-scale (MS)).

EFM calculates three global exciting moments and three global exciting forces at the ship's origin (SO, Figure 2), which is defined as the intersection of a vertical line through the ship's centre of gravity and the plane of the undisturbed free surface of the surrounding water. The global moment equations are used to compute the roll moment (M_x), pitch moment (M_y) and yaw moment (M_z), and the global force equations are used to calculate the surge force (F_{x_surge}), sway force (F_{y_sway}) and heave force (F_{z_heave}).

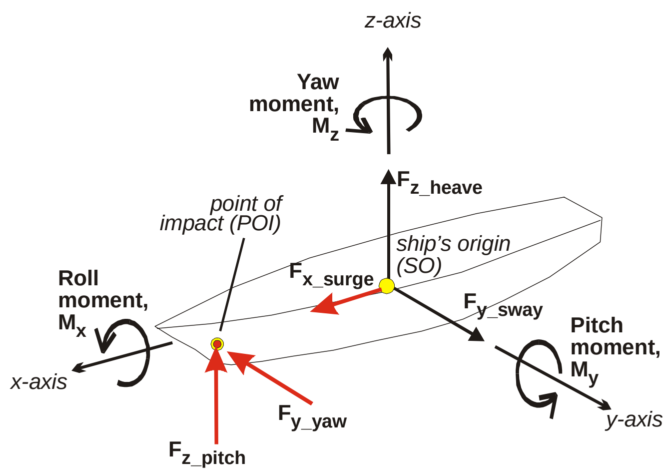

Figure 2. Global exciting moments and global exciting forces calculated by EFM

MOTAN provides two different techniques for calculating impact forces on ships. The first approach uses the pitch, roll and yaw moments to calculate global impact forces at the point of impact (POI, Figure 2). The second approach uses the surge, sway and yaw forces at the ship's origin (SO, Figure 2) to approximate forces at the POI. Note that the two techniques calculate impact forces at different positions on the ship. The first approach calculates forces at the POI and the second approach calculates forces at the SO.

For rigid bodies such as icebreakers, the longitudinal force, F_{x_surge}, at the SO is the same as at the POI. That is because surge motions are equal everywhere along the x-axis of the ship, as shown in Johnston et al. (2004). That is not the case for the lateral and vertical forces, however. If accurate information is available about the distance from the SO to the POI (the moment arm), the global moments M_z and M_y can be used to calculate the lateral and vertical forces at the POI, respectively. Provided the impact location is known with some certainty, it is expected that lateral and vertical forces can be calculated more accurately at the POI (F_{y_yaw}, F_{z_pitch}) than at the SO (F_{y_sway}, F_{z_heave}). That is because the main effects of impacts on the bow are to produce pitch and yaw motions, rather than heave and sway motions at the SO (from which F_{y_sway}, F_{z_heave} are derived). When impacts occur on the bow, heave and sway motions at the SO will be smaller than local heave and sway motions at the POI.

When information about the POI is not available, it may be possible to use F_{y_sway} and F_{z_heave} (at the SO) to approximate F_{y_yaw} and F_{z_pitch} (at the POI). Since the model tests provided well-documented data for 60 controlled impact tests, the results presented in this paper enabled the feasibility of using forces at the SO to approximate those at the POI to be determined.

IMPACT TEST SET-UP

Figure 3 shows the general arrangement that was used for the symmetrical and oblique impacts. The model was directed towards the impact plate from an approach distance of roughly three ship lengths (15 m). Because the model had a displacement of 665 kg, considerable effort was spent planning the test program and designing a reaction support that was suitably stiff (for resisting the ship's impact force) and minimized impact-related vibrations. The L-shaped reaction support was fabricated from steel box channel (254 mm by 254 mm, and 9.5 mm thick). The vertical arm of the support, which was bolted to the overhead carriage, was 1.75 m long, and its side arm extended 1.0 m outwards. The instrumented impact plate was attached to the end of the horizontal arm of the reaction support, as shown in Figure 3.

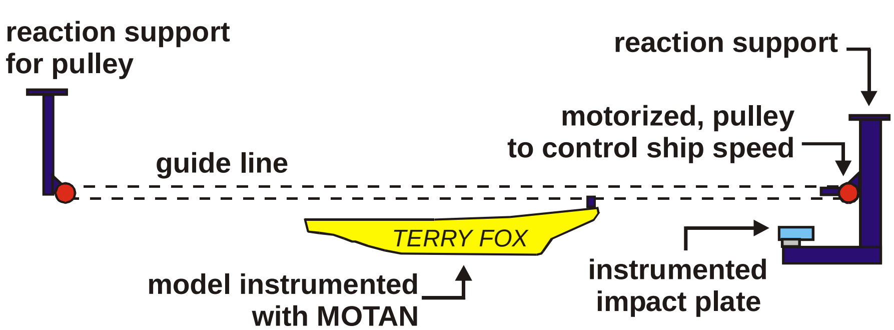

Figure 3 Test configuration used for impacts (length of model 3.44 m)

A motorized pulley controlled the speed of the model during most of the impact tests. The pulley towed the model towards the impact plate, ensuring that the model maintained a constant, controlled speed throughout the test and that it contacted the plate at roughly the same place each time. The guide wires of the pulley were disconnected from the model immediately prior to impact, which allowed the model to coast freely into the impact plate. The impact speed of the model was determined from either the motorized pulley or from the side-looking videotape of the interaction. Tests were conducted at speeds from 0.03 m/s (0.27 kt FS) to 0.55 m/s (5.0 kt FS).

Figure 4 shows the two shapes of impact plates that were used for the tests. The impact plates had an aluminum base, three vertical sides and accepted two sheets of 50 mm thick, rigid foam. Either 100 psi or 60 psi foam was used for the tests, with the foam hardness designated by the manufacturer. The bottom sheet of foam was permanently attached to the plate by bolts and glue, however the top foam sheet was able to be interchanged, should it show evidence of excessive wear. The foam sheets extended 50 mm beyond the base of the metal impact plate to ensure that the model was not damaged during the collisions.

(a) 90° impact plate (b) 45° impact plate

Figure 4 Two types of impact plates used for tests operated with motorized pulley

Symmetrical impacts were conducted with the 90° impact plate shown in Figure 4-a (500 by 410 mm). Oblique impacts on the starboard hull were produced with the 45° impact plate in Figure 4-b (450 x 350 x 740 mm), using a head-on trajectory. A second type of oblique impact was conducted with the modified 90° impact plate. The corners of the rectangular 60 psi foam sheet were clipped until they presented a 40 mm wide face to the approaching model. Ten oblique impacts were conducted against the left corner of the foam sheet and six tests were conducted with the right corner of the foam sheet.

The motorized pulley was used to control ship speed for both the symmetrical tests with the 90° plate and oblique tests involving the 45° impact plate, since the ship's trajectory was in-line with the pulley system. That was not the case for oblique tests against the corners of the rectangular plate however, since they required that the model be manually pushed from a distance of about 15 m. The speed of the model during those tests was obtained from videotapes or digital movies of the interaction.

Global impact forces on the model were measured by MOTAN, which was installed as close as possible to the model's centre of gravity (nearest the SO, where EFM outputs data). Forces on the impact plate were measured using a waterproof AMTI MC6-6-1000 series dynamometer that had been bolted to the underside of the aluminum impact plate. The dynamometer was limited to a force of 2225 N along the x-axis (F_x) and y-axis (F_y), and 4450 N along the z-axis (F_z). The moment capacity of the dynamometer was 340 N-m along the x-axis and y-axis, and 170 N-m along the z-axis.

Both the symmetrical and oblique tests produced an initial impact that corresponded to the first ship-ice contact, followed by a series of hits that occurred as the ship rode-up onto the impact plate. This paper presents results from the initial impact force only, because that is where MOTAN is most appropriate (see Johnston, 2005). Visual records of the interaction were used to determine where the impact occurred on the model's hull, since the distance to the POI is required to calculate forces from the global moments (Figure 2). POIs were forward of Station 18 (shown as "18" in Figure 4) for all the symmetrical and oblique impacts during the initial impact, and moved aft as the ship rode-up onto the impact plate.

RESULTS

Figure 5 compares MOTAN-derived global impact forces on the model to forces measured on the impact plate for the 30 symmetrical and 34 oblique impact tests. Note that the figures show impact forces from MOTAN at two locations: the SO (F_{x_surge}, F_{y_sway} and F_{z_heave}) and the POI (F_{x_surge}, F_{y_yaw} and F_{z_pitch}). Figure 5-a, b, c show data from the 30 symmetrical impacts and Figure 5-d, e, f represent data from the 34 oblique impacts. A dotted line was used to show the 1:1 correlation between the forces measured by each instrument.

Data from Figure 5 were plotted in terms of the percent difference between the two instruments, as calculated by;

$$percent\ diff = \frac{\left|F_{dyno} - F_{MOTAN}\right|}{F_{MOTAN}}\, x\, 100 \qquad (5)$$

where:

F_{dyno} = force measured by dynamometer

F_{MOTAN} = force obtained by MOTAN

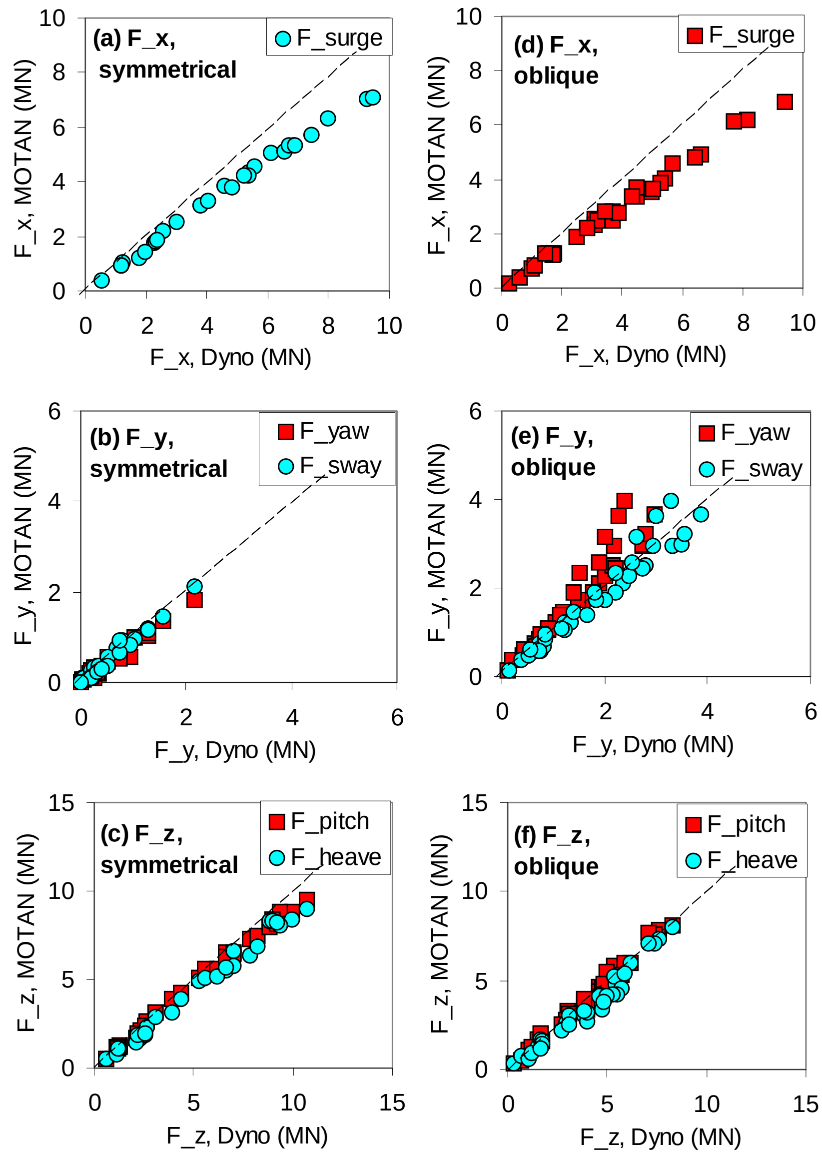

Figure 5 Cross-plots of forces measured by MOTAN and dynamometer during symmetrical impacts (to left) and oblique impacts (to right)

Table 1 summarizes the absolute, average percent difference for each impact type. Only forces that registered higher than 0.5 MN on the dynamometer were used in the calculation, since the accuracy of MOTAN is questionable below that level. Results in Table 1 are categorized according to the impact type. Symmetrical tests with the 90° impact plate were designated as SYM (100 psi foam sheet) and SY (60 psi foam sheet). Oblique impacts with the 45° plate were designated as OBL, and oblique impacts against the corners of the 90° foam sheet were designated as OB and POB tests. Note that results in the table distinguish between the two types of oblique impacts, whereas that distinction was not made in Figure 5.

Table 1 Percent Difference in Forces measured by MOTAN and Dynamometer

Force	Symmetrical (SYM/SY)	Oblique (OBL)	Oblique (OB/POB)
F_x (surge)	20.8%	23.9%	24.1%
F_y (sway)	12.1%	9.6%	10.8%
F_y (yaw)	15.8%	20.1%	23.4%
F_z (heave)	16.0%	7.1%	23.2%
F_z (pitch)	7.2%	6.3%	7.1%

MOTAN consistently yielded a lower longitudinal force than the dynamometer for both the symmetrical and oblique impacts. Table 1 shows that, on average, F_{x_surge} was lower than F_{x_dyno} by 20.8% for the symmetrical impacts, 23.9% for the 45° oblique impacts and 24.1% for the corner-type oblique impacts. The symmetrical impacts resulted in an F_{x_surge} that was considerably smaller, and showed less scatter, than F_{x_surge} for the oblique impacts.

The symmetrical and oblique impacts showed that F_{y_sway} (SO) was a better measure of F_{y_dyno} than F_{y_yaw} (POI). When the force was less than 1.5 MN, there was good agreement between F_{y_sway}, F_{y_yaw} and F_{y_dyno}. Yet, when F_{y_dyno} was higher than about 1.5 MN, F_{y_yaw} yielded higher lateral forces, substantially at times, than measured by the instrumented plate. In general, F_{y_sway} was a better measure of F_{y_dyno} for the three types of impact tests.

F_{z_heave} (SO) and F_{z_pitch} (POI) were good measures of F_{z_dyno} for both the symmetrical and oblique impacts. For the 45° oblique impacts (OBL), F_{z_heave} and F_{z_pitch} had similar percent differences, 7.1% and 6.3% respectively. The symmetrical impacts (SYM/SY) and the corner-style oblique impacts (OB/POB) showed larger percent differences for F_{z_heave} and F_{z_pitch}. F_{z_pitch} was a better measure of F_{z_dyno} during the three different types of impact tests.

CONCLUSIONS

This paper presented results from the model-scale validation work that was undertaken to determine the feasibility of using the MOTAN inertial measurement system to measure full-scale impact forces on ships. This model study had several important outcomes. Results showed that MOTAN, which is a relatively simple system to install, provided a reliable means of measuring impact forces, compared to forces measured independently on an impact plate.

The MOTAN-derived forces that most reliably estimated impact forces on the impact plate were the sway force, the pitch force and the surge force. Percent differences between the two measurement systems ranged from 6.3 to 12.1% for the sway and pitch forces; MOTAN calculated a force that was sometimes higher or lower than forces measured by the dynamometer, depending upon the impact type and the magnitude of impact force. The surge force from MOTAN consistently was about 20% less than the longitudinal force measured by the dynamometer. Most of the discrepancies between forces measured by the two instrumentations were likely due to the appendages being absent from the model during the test program. The hydrodynamic coefficients developed for the full scale *TERRY FOX*, which the MOTAN system uses to calculate global impact forces, took the ship's appendages into account.

Part of this study examined the feasibility of using the forces calculated by MOTAN at the ship's origin to approximate forces at the point of impact, which are expected to be more accurate. Results showed that forces at the ship's origin are comparable to those at the point of impact, at model-scale. That is a significant finding since the impact location (which is needed to calculate global forces at the point of impact) is seldom known during icebreaking operations.

Johnston et al. (2005-a) discuss a second approach to validating MOTAN using full-scale global impact forces measured during the Bergy Bit Impact Trials. Data from the full-scale Impact Trials showed that MOTAN-derived forces were in good agreement with forces measured by two other, independent load measurement systems. Results from both the model-scale test program described here, and the full-scale Bergy Bit Trials indicate that MOTAN is a viable approach to measuring ice-induced global impact forces on ships.

ACKNOWLEDGMENTS

Financial support for this project was provided by the Program of Energy Research and Development (PERD). Particular thanks are extended to B. Hill, A. Bugden, C. Meadus and R. O'Driscoll for their assistance and enthusiasm in conducting the tests. The assistance of A. Wallace in overseeing the swinging of the model and providing line plans of the *TERRY FOX* is appreciated. S. Lafrance spent many hours reviewing video records of the model tests. Thanks to Transport Canada, especially V. Santos-Pedro, for his interest and support in the use of MOTAN over the years.

REFERENCES

Gagnon, R., Cumming, D., Ritch, R., Browne, R., Johnston, M., Frederking, R., McKenna, R., and Ralph, F. (2002) Overview of Bergy Bit Impact Trials. Proceedings IAHR International Symposium on Ice, Dunedin, New Zealand, 2 - 6 December 2002, pp. 458 - 465.

Gagnon, R. (2005) Analysis of Data from Bergy Bit Impacts using a Novel Hull-Mounted External Impact Panel, *submitted to* Journal of Cold Regions Science and Technology.

Johnston, M., Timco, G., Frederking, R. and Miles, M. (2001) Whole-Ship Motions of USCGC *HEALY* as Applied to Global Ice Impact Forces. Proceedings 16th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'01, Ottawa, Canada, pp. 955-964.

Johnston, M., Frederking, R., Timco, G. and Miles, M (2003) MOTAN: A Novel Approach for Determining Ice-Induced Global Loads on Ships. Proceedings MARI-TECH 2003, Montreal, Quebec Canada, 28 – 30 May 2003. 17 pp.

Johnston, M., Frederking, R., Timco, G., and Miles, M. (2004) Using MOTAN to Measure Global Accelerations of the CCGS *TERRY FOX* during the Bergy Bit Trials. Proceedings 23rd International Conference on Offshore Mechanics and Arctic Engineering, OMAE'04, Vancouver, Canada, CD-ROM Paper No. 51239, 8 pp.

Johnston, M. (2005) MOTAN Validation Study: Impact Forces Measured during Tests with the Model-Scale CCGS *TERRY FOX*, Report by Canadian Hydraulics Centre submitted to Program for Energy Research and Development (PERD), CHC-TR-027, October 2004, 36 pp.

Johnston, M., Timco, G., Frederking, R. Miles, M., Ritch, R., Browne, R., Gagnon, R. (2005-a) Comparison of Impact Forces Measured by Different Instrumentation Systems on CCGS *TERRY FOX* during the Bergy Bit Trials, *submitted to* Journal of Cold Regions Science and Technology.

Johnston, M., Timco, G., Frederking, R. Miles, M. (2005-b) Global Loads on CCGS *TERRY FOX* as Determined from an Inertial Measurement System called MOTAN, *submitted to* Journal of Cold Regions Science and Technology.

McTaggart, K. (1997) An Improved Strip Theory Program for Ship Motions and Sea Loads in Waves. 4th Canadian Marine Hydromechanics and Structures Conference (SNAME), Ottawa, June, 1997.

Miles, M. (1986) Measurement of Six Degrees of Freedom Model Motions using Strapdown Accelerometers. Proceedings of the 21st American Towing Tank Conference, Washington, D.C., Aug. 1986. pp. 369 - 375.

Ritch, R., Frederking, R., Johnston, M. and Browne, R. (2005) Local Ice Pressures on a Strain-Gauged Panel During the CCGS *TERRY FOX* Bergy Bit Impact Study. *submitted to* Cold Regions Science and Technology.

Salvesen, N., Tuck, E.O., and Faltinsen, O. (1970) Ship Motions and Sea Loads. Transactions, Society of Naval Architects and Marine Engineers, Vol. 78, pp. 250-287.